

N 70 27019

**NASA TECHNICAL
MEMORANDUM
NASA TM X-53998**

X RADIATION IN BINARY STARS

**CASE FILE
COPY**

By Klaus Schocken
Space Sciences Laboratory

March 13, 1970

NASA

*George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama*

| | | | |
|--|--|--|--------------------------|
| 1. REPORT NO. TM X-53998 | 2. GOVERNMENT ACCESSION NO. | 3. RECIPIENT'S CATALOG NO. | |
| 4. TITLE AND SUBTITLE X Radiation in Binary Stars | | 5. REPORT DATE March 13, 1970 | |
| | | 6. PERFORMING ORGANIZATION CODE | |
| 7. AUTHOR(S) Klaus Schocken | | 8. PERFORMING ORGANIZATION REPORT # | |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812 | | 10. WORK UNIT NO. | |
| | | 11. CONTRACT OR GRANT NO. | |
| | | 13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum | |
| 12. SPONSORING AGENCY NAME AND ADDRESS | | 14. SPONSORING AGENCY CODE | |
| | | | |
| 15. SUPPLEMENTARY NOTES Prepared by Space Sciences Laboratory, Science and Engineering Directorate | | | |
| 16. ABSTRACT The properties of close binary stars and old novae as they are known will be summarized from the literature sources listed in the bibliography. A binary system originates with or results from the splitting of a single star into two components caused by rotational instability during the contraction of the star. The assumption is made that, to become a nova, it is a necessary condition for the star to be a member of a close binary system consisting of a blue and a red star, with a stream of gas flowing from the red to the blue star and forming a shell around the blue star to generate the observed bright emission lines that indicate that this gaseous shell moves with the blue star. Assuming that the explosive process has taken place in the nova, a shock wave will penetrate the surface, forming an expanded atmosphere in a time that is too short for appreciable loss of radiation. When an electric field exists in a plasma with a density such that the electrons whose velocity surpasses a certain critical value will gain more energy from the field than they lose by collisions, runaway electrons will be generated. The hypothesis is made that runaway electrons are the source of deceleration X radiation in the atmosphere of a nova. | | | |
| 17. KEY WORDS | | 18. DISTRIBUTION STATEMENT Announce in STAR. <i>Klaus Schocken</i> | |
| 19. SECURITY CLASSIF. (of this report) Unclassified | 20. SECURITY CLASSIF. (of this page) Unclassified | 21. NO. OF PAGES 17 | 22. PRICE \$ 3.00 |

TABLE OF CONTENTS

| | Page |
|---|------|
| SUMMARY | 1 |
| INTRODUCTION. | 1 |
| THE ORIGIN OF BINARY STARS | 2 |
| NOVAE. | 3 |
| THE EXPLOSIVE PROCESS. | 5 |
| RUNAWAY ELECTRONS | 7 |
| THE IDENTIFIED DECELERATION X-RAY SOURCES | 8 |
| Sco X-1 | 8 |
| Cyg X-2 | 9 |
| Cen X-2 | 10 |
| BIBLIOGRAPHY | 11 |

X RADIATION IN BINARY STARS

SUMMARY

The properties of close binary stars and old novae as they are known will be summarized from the literature sources listed in the bibliography. A binary system originates with or results from the splitting of a single star into two components caused by rotational instability during the contraction of the star. The assumption is made that, to become a nova, it is a necessary condition for the star to be a member of a close binary system consisting of a blue and a red star, with a stream of gas flowing from the red to the blue star and forming a shell around the blue star to generate the observed bright emission lines that indicate that this gaseous shell moves with the blue star. Assuming that the explosive process has taken place in the nova, a shock wave will penetrate the surface, forming an expanded atmosphere in a time that is too short for appreciable loss of radiation. When an electric field exists in a plasma with a density such that the electrons whose velocity surpasses a certain critical value will gain more energy from the field than they lose by collisions, runaway electrons will be generated. The hypothesis is made that runaway electrons are the source of deceleration X radiation in the atmosphere of a nova.

INTRODUCTION

The following stellar X-ray sources have been identified as emitting deceleration (free-free) radiation:

1. Sco X-1
2. Cyg X-2
3. Cen X-2

The properties of close binary stars and old novae as they are known will be summarized in the second, third, and fourth sections from the literature sources listed in the bibliography. In the fifth and sixth sections, the author explains how X rays originate under the physical conditions existing in these objects.

THE ORIGIN OF BINARY STARS

A binary system originates from the splitting of single star into two components caused by rotational instability during the contraction of the star. The most numerous of the close binary systems are contact systems that are observed to form a very compact group of stars with spectral types lying between F0 and G9. Of the systems that have been well determined, the total mass lies between 0.74 and $3.8 M_{\odot}$, and the mass ratio is of the order of 0.5 . Once a collapsing rotating interstellar gas cloud becomes dynamically stable, the surface conditions make the star completely convective with a very high luminosity. The turbulence has the effect to transport energy outward and to mix the star completely. This coupling of the internal and external regions by convection will maintain the star in uniform rotation if the turbulence is isotropic, approximately. The star then contracts, losing matter from the equator, and thereby changing its angular momentum. The star contracts down toward the main sequence, losing mass and angular momentum until it reaches a point where the energy can be transported by radiation, and a radiative core begins to develop. As long as the star was completely convective, turbulence distributed the angular momentum throughout the star so that uniform rotation was a valid approximation. With the growth of the radiative core, the inner regions are no longer coupled to the outer regions, and the star rotates no longer uniformly, even approximately. Each element of the radiative core contracts conserving its angular momentum as the star continues to lose mass from the convective envelope. With the uncoupling of the central regions from the surface by the development of the radiative core, the effect of rotation becomes significant in the central regions. A stability parameter can be calculated at any stage during the subsequent contraction, and if it becomes larger than the limit for stability, the central region will become unstable and split into two parts. It turns out that stars of mass greater than $0.8 M_{\odot}$ will become unstable in the central regions and will possibly split into two stars. The agreement between the lower limit and the observed lower limit of W Ursae Majoris stars, $0.74 M_{\odot}$, is close. It is assumed that after instability, the star splits into two stars that continue to contract, but do not eject matter and therefore conserve total angular momentum. If the system is to form a pair of main-sequence stars, then stars more massive than $4 M_{\odot}$ have too much angular momentum at the onset of instability to form a contact configuration and, assuming angular momentum conservation, they must therefore form a separated system. Stars with $M < 4 M_{\odot}$ can become contact configurations with a common envelope. The agreement between this limit and the observed maximum total mass of W Ursae Majoris stars of $3.8 M_{\odot}$ is satisfactory.

NOVAE

Novae have the following characteristics:

1. The energy of the outburst amounts to 10^{38} joules, approximately.
2. Outbursts are a recurrent phenomenon, the postnova being very similar to the prenova.
3. The prenova is below the main sequence, intermediate between white dwarfs and main sequence stars.
4. The outburst takes place in a very short interval of time; the rise to 2 magnitudes below maximum takes 2 to 3 days (the process itself takes much less time, possibly a few hours); the total increase in luminosity is 11 magnitudes.
5. The star returns to a final stage very similar to the prenova stage.
6. The thermal and gravitational energies of a star of $M = 1 M_{\odot}$ and $R = 1/10 R_{\odot}$ are about 10^{42} joules, total energy radiated $\approx 10^{-4}$ total energy of star, kinetic energy of gas ejected $\approx 10^{-5}$ total energy of star, and mass of gases ejected $\approx 10^{-5}$ mass of star.

The assumption is made that to become a nova it is necessary for a star to be a member of a close binary system consisting of a blue and a red star with a stream of gas flowing from the red to the blue star and forming a shell or disk around the blue star to generate the observed bright emission lines that indicate that this gaseous shell moves with the blue star.

Nonradial oscillations are set up in the blue component by the orbital motion. If resonance conditions are reached between the period of the orbital motion and the period of one of the modes of nonradial oscillations, the amplitude may grow without bound if the damping constant is negative or vanishes. At some time in the evolution of the nova component, the energy sources have to lie close enough to the surface so that the damping constant can vanish.

It is assumed that the prenova has an isothermal core and a hydrogen-burning shell providing the energy radiated by the star. The shell source of the energy is near the surface of the star. The contraction of the isothermal

core was stopped or slowed down when the hydrogen-burning shell source became able to provide the energy radiated away by the star. The temperature in the hydrogen-burning shell is of the order of 10^7 K.

Denoting the number of reactions in the shell per g per sec by p then in the neighborhood of ρ and T , the rate of these reactions varies as ρT^ν . The exponents ν are given as follows with the energy release in MeV.

| | | |
|--------------------------------|--|---------------|
| $p(p, \beta \nu) D^2$ | $\nu_1 = -\frac{2}{3} + \frac{11.27}{T_6^{1/3}}$ | $E_1 = 2.38$ |
| $p(p, D^2) He^3$ | $\nu_2 = -\frac{2}{3} + \frac{12.41}{T_6^{1/3}}$ | $E_2 = 10.98$ |
| $He^3(He^3, 2p) He^4$ | $\nu_3 = -\frac{2}{3} + \frac{41.00}{T_6^{1/3}}$ | $E_3 = 12.85$ |
| $He^3(He^4, \gamma) Be^7$ | $\nu_4 = -\frac{2}{3} + \frac{42.7}{T_6^{1/3}}$ | $E_4 = 1.58$ |
| $Be^7(\beta^-, \nu \gamma) Li$ | $\nu_5 = 0$ | $E_5 = 0.05$ |
| $Li^7(p, \alpha) \alpha$ | $\nu_6 = -\frac{2}{3} + \frac{28.2}{T_6^{1/3}}$ | $E_6 = 17.34$ |

For a given chemical composition of hydrogen and helium, the only variable is the content of He^3 . The effective exponent of the temperature ν_{eff} increases with the content of He^3 . The maximum value of ν_{eff} is reached for the stationary conditions. Using the expressions for ν given in the preceding listing, the result is obtained:

$$\left(\nu_{\text{eff}} \right)_{\text{max}} = -\frac{2}{3} + \frac{28.2}{T_6^{1/3}}$$

The minimum value is obtained for a He^3 concentration $x_3 = 0$, $p_3 = p_4 = 0$:

$$\left(\nu_{\text{eff}}\right)_{\min} = -\frac{2}{3} + \frac{11.27}{T_6^{1/3}}$$

The only important point is the increase in ν_{eff} when the He^3 content increases. Assuming that at some time the He^3 content is low and is increasing, ν_{eff} increases until the star becomes unstable. After an explosion, the He^3 content has decreased, the star is stable again, and the amplitude of the oscillation is finite. The increase in the He^3 content leads back to instability and to a new explosion.

The He^3 content always remains small. During the explosion, the energy liberated comes from the decrease in the He^3 content and from further transformation of hydrogen into helium. The production and destruction of the nuclear fuel give the explanation of the energy output and of the recurrence of the explosions. To explain recurrent explosions, it is necessary to assume that the explosion establishes stability again. This is achieved if the energy generation is caused by thermonuclear reactions and if the instability is caused by a chemical change.

In the double-star hypotheses, the oscillation is increased by the tidal action of a companion. The resonance cannot take place between the orbital motion and the fundamental mode of the nonradial oscillations. The fundamental mode has a much shorter period than the orbital motion. But the nonradial oscillations are divided into compressive modes of shorter period and gravitational modes of longer period. The fundamental mode has a large amplitude near the center of the star. On the other hand, a high gravitational mode has a long period and a high amplitude near the surface.

THE EXPLOSIVE PROCESS

It is not known how the nonlinear explosive process develops. Assuming that the explosive process has taken place, a solution for the propagation of a spherical shock wave in a sphere of gas can be obtained. It is assumed that the energy is released instantaneously and symmetrically at the stellar center. The

mean free path of a photon is so short that the speed of its diffusion is much less than the speed of sound. Then the energy cannot be lost by radiation, but is converted rapidly into thermal and kinetic energy. Any such disturbance can be represented as a superposition of spherical waves. After a short while, all of the wavelets that were converging on the center will be reflected outwards, and the expanding flow will be the total of all these outgoing waves. When the outgoing waves predominate, any variable propagates with the total signal speed:

$$w(p, \rho, T, u) = u + v$$

where u and v denote the fluid and sound speeds, respectively. This includes w . Therefore w can be mapped from itself by displacing each point on a curve a distance proportional to its ordinate. When the gradient becomes vertical, a shock front begins to form. The wavelets immediately behind the shock front overtake and coalesce with the shock rapidly, leading to a stable profile.

When an energy of $\approx 10^{39}$ joules is released at the center of a prenova, the major part of this energy is deposited when the shock is only moderately strong:

$$1 < z < 4$$

$$z = \frac{p_2}{p_1}$$

The values p_1 , p_2 , denoting the pressure just before and behind the shock, are retained by the star, and are not of significance for the outburst itself. When the strength of the shock is appreciable, 10^{38} joules are delivered to those particles crossed by the shock:

$$4 < z$$

Of this amount, nine-tenths will come to rest ultimately as content of an expanded isothermal gas cloud. To provide the momentum required for permanent escape, 10^{37} joules are carried by the shock into the outermost parts of the star. The shock strength necessary for this is:

$$75 < z \qquad \mu = 77$$

μ denoting the Mach number. In addition to the ejection of material by the shock directly, further ejection occurs because the momentum propagated upwards, while the lower layers form an atmosphere. But the entire ejection process takes place in a short time (of the order of minutes), compared with the observed development time of a nova. The formation of the postmaximum shells cannot be attributed to successive ejections.

Radiative cooling and radiative heat transfer may be neglected. After the shock wave has penetrated the surface, the formation of the expanded atmosphere takes place in a time too short for appreciable loss of radiation. Once the layering is complete, cooling will begin in the upper layers. Radiation energy will flow until the nova returns to its original condition with a surface temperature of $50\,000^\circ\text{K}$. The total radiative energy release of a nova is about equal to 10^{38} joules, the same amount of energy that is stored in the atmosphere of $\approx 2 \cdot 10^6$ K.

RUNAWAY ELECTRONS

To analyze the collision phenomena in a plasma, a selected particle — called the "test particle" — is considered as it moves through a background of field particles that are heavy and immobile. These conditions apply, approximately, to an electron moving among ions. In an electric field, the electrons and positive ions drift in opposite directions. If the field is weak enough, the relative drift velocity is much smaller than the thermal velocity of the electrons, and its value is determined by the requirement that in equilibrium the friction of the electrons against the ions just compensates the accelerating force from the electric field.

In a strong electric field, the electron velocity distribution can differ from a Maxwellian distribution, in weakly as well as highly ionized plasmas.

Even in the absence of a strong field, some very fast electrons exist in the tail of the distribution that lose less momentum by friction against the ions than they gain from the electric field. Since they collide with other electrons infrequently, they are decoupled from the main body of the electron population and run away independently, even in a weak field.

When an electric field exists in a plasma with a density such that the electrons whose velocity surpasses a certain critical value will gain more energy from the field than they lose by collisions, runaway electrons will be generated. Since the collision cross section decreases with increasing energy, these electrons follow the lines of force in the plasma and continue to gain energy as long as a longitudinal electric field exists. The maximum energy to which these electrons can be accelerated is determined by the drift across the lines of force.

Experimentally, the runaway effect has been observed in the stellarator and the betatron, where the runaway electrons impinge on the wall finally and produce deceleration X radiation. In addition, intense microwave generation has been observed.

The hypothesis is made that runaway electrons are the source of deceleration X radiation in the atmosphere of a nova.

THE IDENTIFIED DECELERATION X-RAY SOURCES

Sco X-1

Sco X-1 is a 12th-magnitude variable star resembling an old nova. Together with another star supplying mass to it, it forms a close binary system.

The X-radiation is produced by free-free transitions in pure hydrogen with an electron temperature around 5×10^7 K. In the near infrared spectral region, the gas is opaque and radiates as a black body also with a temperature of 5×10^7 K. All the radiation is produced by the same mass of gas, assumed to be a sphere. The pulsational character of the light variation and the color variations indicate that at least a large part of the optical radiation cannot be the optical extrapolation of deceleration radiation emitted by an optically thin layer of hot plasma with $T \approx 5 \times 10^7$ K and ion density $\approx 10^{22} \text{ m}^{-3}$.

The approximate central mass is $0.1 M_{\odot}$ if Sco X-1 is at a distance of 300 pc. At this distance, the object radiates 2×10^{29} watts and the rate of accretion is $2 \times 10^{-6} M_{\odot} \text{y}^{-1}$. This mass could be supplied by another star, and the two stars together form a close binary system. The source is a plasma cloud with radius $\approx 0.01 R_{\odot}$.

The majority of the observations form a mean light curve with a period of 0.5276^d , with an amplitude of 0.75 magnitude in blue light, and with an asymmetry of 0.7 (the fraction of the light curve occupied by the descending branch).

Cyg X-2

The optical variability on a time scale of several minutes and spectrographic data establish the object as a spectroscopic binary of short period. The system may be a contact binary and may be an eclipser. It must be classified as a Population II object.

The early type component is either flat or earlier than a normal 09V, while the later type spectrum has to be later than F2V. Variations of 0.3 magnitude occur between successive nights. The observed magnitudes are brighter than an extrapolated deceleration radiation spectrum fitted to the X-ray data. Most of the optical light of the system is not from the free-free continuum of the hot plasma responsible for the X rays. The oscillations are peaked, relatively short, and of amplitude of about 0.04 magnitude, with rise and fall times of the order of 3 minutes, separated by about 11 minutes. These are superposed on a larger term fluctuation of about 1 hour, of amplitude 0.10 magnitude, and superposed in turn on a gradual decline of about 15 percent over the 5-hour interval. The spectrum is definitely nonwhite. Significant energy resides in frequency components of 4 minutes or less, superposed on larger period fluctuations of the order of 1 hour. A possibility for most of the visible light of the system is the pulsation of one of the stellar components of the system, similar to DQ Her. The masses of the components are approximately equal. A lower limit for the relative speed of the binary components is about 300 km sec^{-1} . For stars with masses $\approx 1 M_{\odot}$ and separations $\approx 10^9 \text{ m}$, as is probably the case for Cyg X-2, X-ray emission is the major mechanism of energy dissipation in the binary. The total energy in Cyg X-2 is about 10^{41} joules.

Cen X-2

Cen X-2 is a highly variable X-ray star, very similar to a nova emitting in the visible spectrum. The source gives recurring X-ray outbursts, every outburst lasting probably for a short period of time. It may be an expanding, constant-mass plasma. A dense plasma cloud of radius $\approx 10^{12}$ m is heated at constant volume to nearly 2×10^7 K and then proceeds to expand isothermally and to cool off. The recurring short-lived outbursts can be attributed to a shock wave from the nova outburst expanding into the circumstellar medium. Such a shock could accelerate and heat the gas to a high temperature as it propagates into a medium of decreasing density.

BIBLIOGRAPHY

Alven, H. ; and Faelthammar, C. G. : Cosmical Electrodynamics. Clarendon Press (Oxford), 1963.

Chodil, G. , et al. : Simultaneous Observations of the Optical and X-Ray Spectra of Sco XR-1. *Astrophys. J.* , vol. 154, 1968, pp. 645-654.

Glasby, J. S. : Variable Stars. Harvard U. Press, (Cambridge, Mass.), 1969.

Hazelhurst, J. : The Shock-Wave Theory of Novae. *Adv. Astron. Astrophys.* , vol. 1, 1962, pp. 1-45.

Johnson, H. M. ; and Stephenson, C. B. : A Possible Old Nova Near Sco X-1. *Astrophys. J.* , vol. 146, 1966, pp. 602-605.

Kraft, R. P. : Cataclysmic Variables as Binary Stars. *Adv. Astron. Astrophys.* , vol. 2, 1963, pp. 43-85.

Kristian, J. ; Sandage, A. ; and Westphal, J. A. : Rapid Photometric and Spectroscopic Variations of the X-Ray Source Cyg X-2. *Astrophys. J.* , vol. 150, 1967, pp. L99-L105.

Neugebauer, G. , et al. : A Study of Visual and Infrared Observations of Sco XR-1. *Astrophys. J.* , vol. 155, 1969, pp. 1-9.

Peimbert, M. , et al. : Photoelectric Scanner Spectrophotometry of Cyg X-2. *Astrophys. J.* , vol. 151, 1968, pp. L93-L97.

Prendergast, K. H. ; and Burbidge, G. R. : On the Nature of Some Galactic X-Ray Sources. *Astrophys. J.* , vol. 151, 1968, p. L83-L88.

Rao, U. R. , et al. : X-Ray Flux from Centaurus X-2 in the Energy Range 2-20 keV. *Astrophys. J.* , vol. 157, 1969, pp. L127-L132.

Schatzman, E. : Theory of Novae and Supernovae. *Stellar Structure*, L. H. Aller and D. B. McLaughlin, ed. , U. of Chicago Press, 1965, pp. 327-365.

van Genderen, A. M. : Five-Color Photometry of the X-Ray Source Sco X-1. *Astron. and Astrophys.* , vol. 2, 1969, pp. 6-17.

APPROVAL

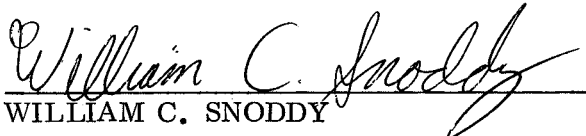
TM X-53998

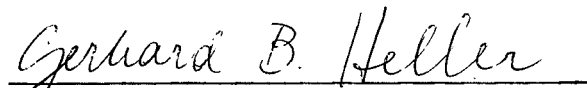
X RADIATION IN BINARY STARS

By Klaus Schocken

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.


WILLIAM C. SNODDY
Chief, Space Thermophysics Division


GERHARD B. HELLER
Director, Space Sciences Laboratory

DISTRIBUTION

TM X-53998

INTERNAL

DIR

AD-S

Dr. Ernst Stuhlinger

S&E-DIR

Mr. Hermann Weidner

S&E-R

Dr. William Johnson

PD-MP

Mr. James Downey

S&E-AERO-T

Dr. Helmut Krause

S&E-SSL-DIR

Mr. Gerhard Heller

Mr. Ray Hembree

S&E-SSL-X

Dr. Rudolf Decher

Mr. Hoyt Weathers

S&E-SSL-C

Mr. James Mathis

Reserve (15)

S&E-SSL-N

Mr. Henry Stern

S&E-SSL-S

Dr. Werner Sieber

S&E-SSL-P

Mr. Robert Naumann

S&E-SSL-T

Mr. William Snoddy

Dr. Klaus Schocken (10)

S&E-SSL-TE

Mr. Ed Miller

Mr. Harry Atkins

Mr. Walter Fountain

Mr. James Fountain

Mr. Stanley Fields

Mr. John Reynolds

Mr. Charles Baugher

Mr. Ed Reichmann

Mr. Robert Wilson

S&E-SSL-TT

Mr. Billy Jones

Mr. Daniel Gates

Mr. Paul Craven

Mr. Jimmy Watkins

Dr. Mona J. Hagyard

Mr. Ted Calvert

Dr. Gilmer Gary

S&E-SSL-TR

Mr. Gary Arnett

Mr. Tommy Bannister

Dr. Roger Kroes

Mr. Roger Linton

Mr. Donald Wilkes

Mr. James Zwiener

Miss Barbara Richard

Dr. Ulrich Wegner

Dr. Kulshreshtha

DEP-T

INTERNAL (Concluded)

A&TS-PAT

Mr. L. D. Wofford, Jr.

PM-PR-M

A&TS-MS-IP (2)

A&TS-MS-IL (8)

A&TS-TU (6)

A&TS-MS-H

EXTERNAL

National Aeronautics and Space Administration

Washington, D. C. 20546

Attn: Dr. A. Boggess, Code 613

Dr. K. Hallan, Code 613

Dr. T. Stecher, Code 613

Dr. J. Underwood, Code 614

Dr. E. Boldt, Code 611

Manned Spacecraft Center

Houston, Texas 77058

Attn: Dr. Yoji Kondo, TG4

Scientific and Technical Information Facility (25)

P. O. Box 33

College Park, Maryland 20740

Attn: NASA Representative (S-AK/RKT)